



Soil physical properties associated with the invasive spotted knapweed and native grasses are similar

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Abstract

Centaurea maculosa Lam. (spotted knapweed), a Eurasian perennial forb, has invaded disturbed and undisturbed semiarid grasslands in the western United States. In the past, success in controlling *C. maculosa* and restoring invaded areas has been limited. Most research has addressed chemical aspects of invasive species interactions with soils, while potential impacts of altered soil physical properties on *C. maculosa*'s success has not been studied. We hypothesized that the persistence of *C. maculosa* in semiarid rangelands might reflect an ability to alter site conditions. The objective of this study was to compare selected soil physical properties under *C. maculosa*-dominated and native perennial grass-dominated areas on semiarid grassland. We used six field sites in western Montana containing adjacent plots dominated by *C. maculosa* and by native perennial grasses. Soil physical properties including particle size fractions, bulk density, and hydraulic and thermal properties, as well as total organic carbon content, of near-surface soils were measured for each vegetation type. Soil physical properties seldom differed between *C. maculosa*- and native grass-dominated areas. When soil physical properties differed, the differences were inconsistent within and among sites. Presence of *C. maculosa* did not alter surface soil characteristics at our six sites, thus its persistence on these semi-arid grasslands cannot be explained by an ability to alter near-surface soil characteristics.

Abbreviations: LAI – leaf area index

Introduction

Centaurea maculosa Lam. (spotted knapweed), a Eurasian perennial forb (Boggs and Story, 1987; Chicoine et al., 1985), invades grasslands and open woodlands in arid and semiarid regions in western North America, and forms dense stands that inhibit the growth of other species (Fletcher and Renney, 1963; Tyser and Key, 1988; Watson and Renney, 1974). Although usually associated with disturbance, *C. maculosa* is spreading onto undisturbed, pristine grasslands (Lacey et al., 1990; Tyser and Key, 1988).

Wildlife habitat has been altered and millions of dollars in livestock forage have been lost (French and Lacey, 1983; Hirsh and Leitch, 1996).

Success in controlling *C. maculosa* and restoring invaded areas to native species has been limited. Several mechanisms may allow *C. maculosa* to persist including altering site conditions, or preempting soil resources such as water or nutrients which are frequently limiting in semiarid grasslands (Fowler, 1986). Several plant species alter soil properties, favoring their own growth and reproduction (van Breemen and Finzi, 1998). Potential vegetative impacts on soil chemical and biological properties have received considerable attention (e.g., Inderjit et al., 1997; Olson and Wal-

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lander, 2002), but we could find relatively little information linking invasive plants and soil physical properties.

C. maculosa's growth form and phenology differ from those of adjacent native grasses, which may result in altered soil physical properties. In semiarid grasslands, most native grasses have fibrous root systems that are densely distributed in the upper 30 cm of the soil profile (Dobrowolski et al., 1990; Weaver, 1919), whereas *C. maculosa* has a deep tap-root which may access resources deeper in the soil profile (Watson and Renney, 1974). Potential differences in organic carbon distribution, e.g., from root turnover, from these disparate root systems might influence soil properties or processes that influence plant success.

Changes in plant community structure may alter near-surface soil properties which could impact root growth, seedling emergence and growth, soil water and nutrient uptake (Hamblin, 1985), or heat capacity (Oades, 1984; Smith et al., 1987). For example, seed germination, seedling emergence, root growth, and plant production are affected by soil temperature (Hillel, 1998; Singh and Sainju, 1998), thus a more extreme near-surface soil thermal environment in *C. maculosa*-dominated areas could negatively affect seed germination and seedling growth of native grasses. Changes in plant community structure may also alter near-surface soil properties which affect water holding capacity and infiltration. *C. maculosa*-dominated sites appear to have greater surface runoff and erosion (French and Lacey, 1983; Lacey et al., 1989), but evidence for this is largely anecdotal. If invasive species substantially alter near-surface soil properties, and if such changes persist after eradicating the invasive plant, restoring such sites to native species would require amending these soils.

The objective of this study was to determine whether near-surface soil physical properties differed between adjacent areas dominated by *C. maculosa* and by native grasses. We compared particle size fractions, bulk density, hydraulic properties, thermal properties, and total organic carbon content of near-surface soils from these areas. Soil carbon content, a chemical attribute, was evaluated because it strongly influences many physical properties and processes and thus had potential utility in explaining any measured differences in these properties.

Materials and methods

Study sites

Six field sites in western Montana were selected (Table 1). At five sites we established four blocks consisting of two nearly-adjacent paired 2 m² plots. One site (Thiede) contained eight blocks of 1 m² paired plots. One plot dominated by *C. maculosa* (>50% *C. maculosa* canopy cover) and one plot dominated by native grasses (<10% *C. maculosa* canopy cover) were selected in close proximity to minimize effects associated with spatial heterogeneity of soil properties, physiography, and inherent site differences. Soil pits excavated at the Helena, Belgrade, and Hyalite sites confirmed that soil profiles and taxonomy were similar in *C. maculosa*, and native grass-dominated areas (Sperber, 2001). We measured leaf area index (LAI; LAI-2000, LiCOR, Lincoln, Nebraska, USA), and estimated basal cover for *C. maculosa* and native grasses by growth form (bunch- or tussock-grass, rhizomatous grass, annual grass) in multiple sample frames in each plot at the Helena, Belgrade, and Hyalite sites 3–5 August 1999 and 28 July to 4 August 2000.

Site selection criteria were as follows: (1) *C. maculosa* present for at least 5–10 years; (2) *C. maculosa*-dominated areas intermixed with or intergrading to areas dominated by native perennial grasses; (3) lack of previous site disturbance that may have caused differences in soil properties; (4) little or no active grazing or herbicide use; (5) at least 10–15 cm of surface soil with low rock content; and (6) reasonably level terrain. Criteria 1–4 defined the vegetation types, and minimized potential for confounding of plant effects with site history. Criteria 5 and 6 were related to measurement constraints.

Thiede was grazed heavily until the 1980s. Helena had not been grazed, leading to large amounts of litter present in *C. maculosa*, and native grass-dominated areas. The *C. maculosa* areas had large amounts of fallen 'stalk' litter compared with the finer, leaf litter characteristic of the native grass-dominated areas. Belgrade had a history of light grazing by horses. Plots at this site were fenced to prevent grazing in the study area. Hyalite had not been grazed since the 1970s. Sheep grazed Loch Leven until the 1980s. Cottonwood had recently been grazed lightly by cattle.

We aged 5–10 *C. maculosa* plants at each site, except Thiede, to indicate the minimum number of years that *C. maculosa* has been present on the site (Boggs

Table 1. Study site descriptions including soils, slope, mean annual precipitation (Western Regional Climate Center [WRCC], 2000), and dominant native grasses

Site	Soils	Slope (%)	Mean annual precipitation (mm)	Native grasses
Thiede	Nesda loams	3–5	425	<i>Festuca idahoensis</i> <i>Elmer</i> ; <i>Pascopyrum</i> <i>smithii</i> (Rydb.) Löve
Helena	Rothiemay loams	1–2	285	<i>Pseudoroegneria spicata</i> (Pursh) Löve, <i>Stipa</i> <i>comata</i> Trin. & Rupr.
Belgrade	Kassler gravelly coarse sandy loams	0–1	360	<i>P. smithii</i>
Hyalite	Hyalite loams	0–1	465	<i>F. idahoensis</i> , <i>P. smithii</i>
Loch Leven	Beaverell gravelly loams mixed with Attewan loams	0–1	424	<i>S. comata</i> , <i>P. spicata</i> , <i>P.</i> <i>smithii</i>
Cottonwood	Beaverton gravelly loams	0–1	573	<i>S. comata</i> , <i>F. idahoensis</i> , <i>P. smithii</i>

and Story, 1987). The average age of *C. maculosa* plants was 4 – 5 years. For most sites, landowners or county weed supervisors indicated that *C. maculosa* had been present several decades.

Basic soil properties

We measured near-surface soil properties including particle size fractions (sand, silt, clay; Soil Survey Staff, 1975), bulk density, and total organic carbon content. We collected 48-mm diameter soil cores at the 0–60 mm depth for particle size fractions at Helena, Belgrade and Hyalite, and at the 0–50 mm depth for the other variables at all sites.

Soils were oven-dried (105 °C) and sieved (2 mm) before processing; samples used for organic C measurement were air- rather than oven-dried. We measured particle size fractions using the modified Day hydrometer method (Gee and Bauder, 1986). Volumetric soil cores were used to determine dry bulk density (Blake and Hartge, 1986). Total organic carbon content was estimated by combustion (CNS-2000, LECO Corp., St. Joseph, Missouri, USA), following confirmation of negligible inorganic carbon contents for our soils (Nelson and Sommers, 1986).

Bulk density was calculated on four soil cores for each plot (two soil cores per plot at Thiede). Particle size fractions and total organic carbon content were measured on two composite soil samples per plot at

Helena, Belgrade, and Hyalite, four composite soil samples per plot at Loch Leven and Cottonwood, and two soil samples per plot at Thiede.

Soil hydraulic properties

Soil hydraulic properties govern the entry of water at the soil surface, and subsequent movement of water in the soil profile. Differences in soil hydraulic properties might thereby impact the amount and timing of plant-available soil water, potential for surface runoff and erosion, and other processes important to a site's suitability for invasive or native plants. We measured near-steady state infiltration rates using tension disk permeameters (Soil Measurement Systems, Tucson, Arizona, USA; Perroux and White, 1988) at four supply pressures (i.e., matric potentials) of –0.03, –0.06, –0.09, and –0.15 m at each soil location at Thiede in the fall of 1998. Steady infiltration rates at supply pressures of –0.03, –0.06, and –0.15 m were measured at Helena, Belgrade, and Hyalite during the 1999 field season. Supply pressures of –0.02, –0.04, –0.06, and –0.15 m were used at Loch Leven and Cottonwood during the 2000 field season. A pressure transducer connected to a datalogger (CR23X, Campbell Scientific, Inc., Logan, UT) measured water outflow from the permeameters at 10 s intervals during 30 – 45 min runs. We measured infiltration at two locations in each plot at all field sites except Thiede, where we meas-

ured infiltration at one location in each of five paired plots.

Infiltration rates were estimated using linear regression of measured cumulative infiltration (m) vs. time (s) for the last 5 min at each supply pressure. Best-fit estimates of saturated hydraulic conductivity (K_s ; m s^{-1}) and the variable α (m^{-1}) in Gardner's (1958) hydraulic conductivity model were determined using nonlinear least-squares optimization (Wraith and Or, 1998) of measured infiltration rates to Wooding's (1968) solution for three-dimensional infiltration from shallow circular ponds:

$$\frac{q}{\pi r^2} = K_s e^{\alpha h} \left(1 + \frac{4}{\pi \alpha r} \right), \quad (1)$$

where q is the final infiltration rate ($\text{m}^3 \text{s}^{-1}$), r is radius (m) of fine sand contact material between the infiltrometer disk and the soil surface, and h is the water supply potential (-m).

Soil thermal properties

Soil thermal properties along with local climatic factors govern near-surface soil temperature conditions that are critical to seed and seedling establishment. Volumetric heat capacity (c_v) was calculated as the sum of the heat capacities of the mineral, water, and organic matter soil components multiplied by their respective volume fractions:

$$C_v = \sum_i \rho_i \varphi_i c_i = \rho_m \varphi_m c_m + \rho_w \varphi_w c_w + \rho_{om} \varphi_{om} c_{om}, \quad (2)$$

where ρ_i is the density of soil constituents (m = mineral, w = water, and om = organic matter), φ_i is the volume fraction, and c_i is the specific heat per unit mass (Campbell and Norman, 1998; Hillel, 1982). We converted total organic carbon content to organic matter content by multiplying by 1.7 (Nelson and Sommers, 1982). Values of specific heats and densities used in these calculations were $733 \text{ J kg}^{-1} \text{ K}^{-1}$ and 2650 kg m^{-3} for soil minerals, $1926 \text{ J kg}^{-1} \text{ K}^{-1}$ and 1300 kg m^{-3} for soil organic matter, and $4182 \text{ J kg}^{-1} \text{ K}^{-1}$ and 1000 kg m^{-3} for water (Brutsaert, 1982). Density and specific heat of air are negligible in comparison and were not considered.

Thermal conductivity of near-surface soils (0–0.06 m) was estimated using a line-source heat sensor (Soiltronics, Burlington, WA; Shiozawa and Campbell, 1990). Thermal conductivity depends on soil water content and is sensitive to thermal gradients,

thus half of the sample locations were wetted by ponding water within a 0.22 m diameter ring, then covered with 0.04 m thick styrofoam boards, and allowed to drain for about 1 d. Sample locations that were not wetted were also covered with styrofoam boards to equilibrate temperatures for about 1 d before we measured thermal conductivity.

Volumetric water content ($\text{m}^3 \text{m}^{-3}$), bulk density (Mg m^{-3}), and total organic carbon content (g kg^{-1}) were determined by coring the soil (spanning the 0–0.05 m depth) where the heat sensor had been inserted. These soil cores were also used to determine particle size fractions at Loch Leven, Cottonwood, and Thiede. Thermal conductivity was calculated for the heating period following Shiozawa and Campbell (1990):

$$T - T_o = \frac{q}{4\pi\lambda} [\ln(t) + d], \text{ for } t < t_1, \quad (3)$$

where T is sensor temperature (K), T_o is initial temperature, q is heat production per unit time and unit length of the source (W m^{-1}), λ is thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$), t is time (s), d is a constant, and t_1 is time when heating is stopped. We estimated the soil thermal property apparent thermal diffusivity as the ratio of thermal conductivity to volumetric heat capacity (Campbell and Norman, 1998).

To characterize the near-surface soil temperature regime, we buried copper-constantan thermocouples at Helena, Belgrade, and Hyalite in May 1999. Thermocouples were installed in two blocks at each site. A datalogger connected to a signal multiplexer (21X and AM416, Campbell Scientific, Inc., Logan, Utah, USA) monitored soil temperatures at 0.025, 0.05, and 0.15 m depths at 0600, 1200, 1800, and 2400 h. Because we had only two datalogger systems, each site was monitored for variable lengths of time during the 1999 field season. We monitored Helena and Hyalite continuously during the 2000 field season.

Soil temperatures at 0.025, 0.05, and 0.15 m depths were fitted to a sinusoidal heat flow model to estimate the thermal damping depths, mean daily surface temperatures, and daily amplitudes of surface soil temperature variation (Campbell and Norman, 1998):

$$T(z, t) = T + A_o e^{\frac{z}{d}} \sin \left[\omega(t - 8) + \frac{-z}{d} \right], \quad (4)$$

where T is temperature ($^{\circ}\text{C}$) of the soil as a function of depth (z ; m) below the surface and time (t ; h), T is the mean daily soil surface temperature ($^{\circ}\text{C}$), A_o is the mean amplitude ($^{\circ}\text{C}$) of surface soil temperature fluctuations, d is the characteristic thermal damping depth (m), ω is the angular frequency (h^{-1}) equal to

$2\pi/P$, and P is the temperature oscillation period of 24 h. Consecutive days with stable weather conditions were used to estimate d , T , and A_0 .

Data analysis

Descriptive statistics were used to summarize basal cover and leaf area indices. Mean soil properties for each plot were compared between vegetation types using analysis of variance (ANOVA; SAS, 2000). Mean K_s and α values were compared between native grass and *C. maculosa* plots within sites using ANOVA. We transformed Loch Leven K_s values and Belgrade α values using the natural log because of unequal variances as indicated by residual plots.

Mean plot values of volumetric heat capacity, thermal conductivity, and apparent thermal diffusivity for each vegetation type, and wetted or ambient soil conditions were compared within sites using split plot (wetted, ambient) ANOVA (SAS, 2000). Thermal diffusivities for Thiede were transformed (natural log) because variances were not equal as indicated by residual plots. Analysis of covariance was used to compare mean damping depth between vegetation types; mean soil water content was the covariate (SAS, 2000). We compared the amplitude of surface soil temperature fluctuations using ANOVA. We conducted a nonparametric rank F test on mean daily surface soil temperatures because the distribution was not normal (Neter et al., 1996). Because of the very high inherent degree of spatial variability associated with soil properties and processes (Mulla and McBratney, 2000), a significance level of $P \leq 0.10$ was selected for all comparisons.

Results

Vegetation

Total basal cover was greater for *C. maculosa* plots than for native grass plots at Belgrade in 1999 and 2000 (Table 2). While total basal cover at Belgrade was similar both summers, total basal cover at Helena and Hyalite was lower in 2000 than in 1999. *C. maculosa* plots at Hyalite had lower *C. maculosa* cover relative to the other sites. Native grass cover was lower in *C. maculosa* plots than in native grass plots.

Our measure of leaf area index could not differentiate between living material and standing dead culms, and included all material ≥ 0.03 m above the soil

surface. LAI in *C. maculosa* plots was higher than in native grass plots at all three sites in 1999 and 2000 (Table 2).

Basic soil physical properties

C. maculosa and native grass plots had similar near-surface soil particle size fractions at most sites. Helena and Belgrade had greater (by about 4%; $P=0.07$ and 0.10 for Helena and Belgrade, respectively) sand fraction in *C. maculosa* plots than in native grass plots. This difference was consistent among all the plots at these sites. Silt and clay size soil fractions were similar between vegetation types at all sites.

Native grass plots had higher near-surface soil bulk densities than *C. maculosa* plots at Helena ($P=0.02$; $n = 4$). Trends in bulk density between vegetation types were inconsistent among blocks for the remaining sites, and inconsistent across sites.

Mean near-surface soil organic carbon contents ranged from 16 to 70 g kg⁻¹. At Loch Leven, *C. maculosa* plots had higher total organic carbon contents (18.6 ± 0.8 g kg⁻¹) than native grass plots (16.7 ± 0.9 g kg⁻¹; $P=0.09$; $n = 4$). However, differences in total organic carbon content between vegetation types at all other sites were inconsistent among blocks.

Soil hydraulic properties

Saturated hydraulic conductivity (K_s) and the α coefficient, which is related to the range in water conducting pore sizes, were similar between vegetation types at all sites (Figure 1). Measured K_s was highly variable and ranged from 0.0004 to 0.0085 m h⁻¹. Similarly, the α coefficient was highly variable and ranged from 0.0008 to 0.0021 m⁻¹. Variation of K_s and α between vegetation types was inconsistent among blocks at most sites, and among sites.

Soil thermal properties

Near-surface soil volumetric heat capacity did not differ between vegetation types at any of the six field sites (Figure 2). Differences in soil thermal conductivity between vegetation types were inconsistent among sites. At Helena, native grass plots had higher near-surface soil thermal conductivity, while the opposite result was found at Thiede; no differences were measured at the remaining sites. Apparent soil thermal diffusivity differed between vegetation types only at Cottonwood and Thiede, with native grass plots hav-

Table 2. Basal cover (mean \pm SE; $n=4$) by *C. maculosa* and grass growth forms and leaf area index (LAI; mean \pm SE; $n=4$) in *C. maculosa* (CEMA) and native grass plots in 1999 and 2000. Identical mean and SE in some cases results from a growth form being found in only one of the four paired plots

Site	Plot	Year	Basal cover (%)					LAI
			<i>C. maculosa</i>	Bunch grass	Rhizom. grass	Annual grass	Total	
Helena	CEMA	1999	6.9 \pm 1.4	3.8 \pm 0.9	0.4 \pm 0.3	0.09 \pm 0.09	11.3 \pm 1.0	1.4 \pm 0.3
		2000	2.4 \pm 0.3	1.4 \pm 0.1	0.2 \pm 0.1	–	4.0 \pm 0.2	1.1 \pm 0.2
	Grass	1999	0.2 \pm 0.2	7.8 \pm 3.1	0.5 \pm 0.4	1.8 \pm 0.8	10.3 \pm 2.9	0.9 \pm 0.3
		2000	0.2 \pm 0.2	3.4 \pm 0.9	0.1 \pm 0.1	0.2 \pm 0.1	3.9 \pm 1.0	0.8 \pm 0.2
Belgrade	CEMA	1999	4.4 \pm 1.0	–	0.3 \pm 0.1	0.2 \pm 0.1	4.9 \pm 0.9	0.7 \pm 0.1
		2000	3.4 \pm 0.6	0.1 \pm 0.1	0.9 \pm 0.2	0.03 \pm 0.03	4.4 \pm 0.5	0.9 \pm 0.1
	Grass	1999	0.04 \pm 0.04	–	0.7 \pm 0.1	0.3 \pm 0.2	1.0 \pm 0.2	0.3 \pm 0.1
		2000	0.4 \pm 0.2	–	1.8 \pm 0.3	0.2 \pm 0.1	2.3 \pm 0.4	0.6 \pm 0.1
Hyalite	CEMA	1999	1.4 \pm 0.5	11.6 \pm 3.8	0.2 \pm 0.2	–	13.3 \pm 3.1	0.9 \pm 0.1
		2000	1.1 \pm 0.2	3.9 \pm 0.5	0.4 \pm 0.3	0.03 \pm 0.03	5.4 \pm 0.4	1.1 \pm 0.1
	Grass	1999	–	16.1 \pm 5.1	0.2 \pm 0.2	–	16.3 \pm 5.0	0.6 \pm 0.1
		2000	0.06 \pm 0.06	5.1 \pm 0.8	0.06 \pm 0.06	–	5.2 \pm 0.7	0.9 \pm 0.1

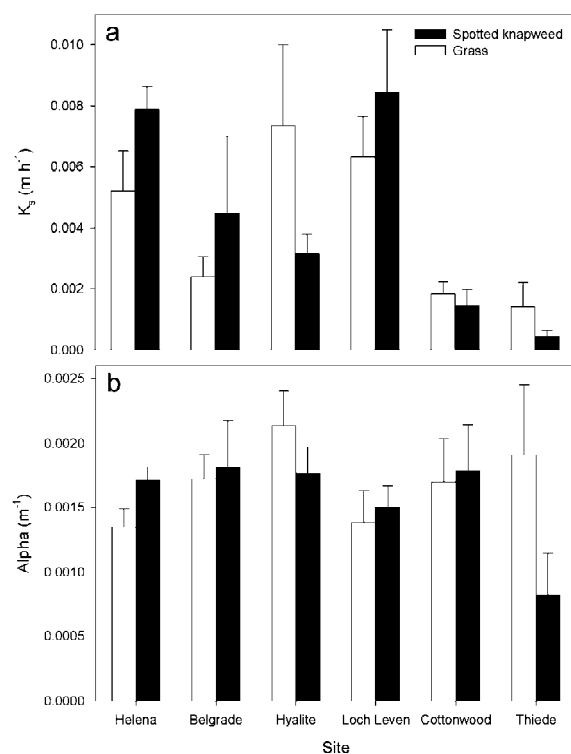


Figure 1. (a) Saturated hydraulic conductivity (K_s ; mean \pm SE; $n=4$; Thiede $n=5$) and (b) alpha (mean \pm SE; $n=4$; Thiede $n=5$), a hydraulic parameter related to the range in water conducting pore sizes, for *C. maculosa* and native grass plots.

ing greater thermal diffusivity at Cottonwood, but *C. maculosa* plots having greater thermal diffusivities at Thiede. Mean thermal damping depths across a range of soil water contents ranged from 0.05 to 0.08 m and differed between native grass and *C. maculosa* plots at Helena ($P=0.01$; $n=2$) and Belgrade ($P<0.001$; $n=2$). Similar to the lack of a systematic pattern for the other soil thermal properties, the direction of measured differences with respect to the two vegetation types was opposite at these two locations.

At Belgrade and Hyalite, native grass plots had higher mean daily soil surface temperatures (Belgrade: $20.2 \pm 0.5^\circ\text{C}$, $P=0.05$; Hyalite: $17.9 \pm 0.3^\circ\text{C}$, $P=0.01$) than *C. maculosa* plots (Belgrade: $18.7 \pm 0.5^\circ\text{C}$; Hyalite: $17.0 \pm 0.3^\circ\text{C}$). At Hyalite, the mean amplitude of soil surface temperature fluctuations (A_0) was greater for native grass plots ($11.3 \pm 0.5^\circ\text{C}$, $P=0.003$) than *C. maculosa* plots ($9.8 \pm 0.3^\circ\text{C}$). Differences in A_0 between vegetation types were inconsistent among sites.

Discussion

Differences in soil particle size fractions, bulk density, total organic carbon content, saturated hydraulic conductivity, the range in water conducting pore sizes (α), and soil thermal properties between vegetation types

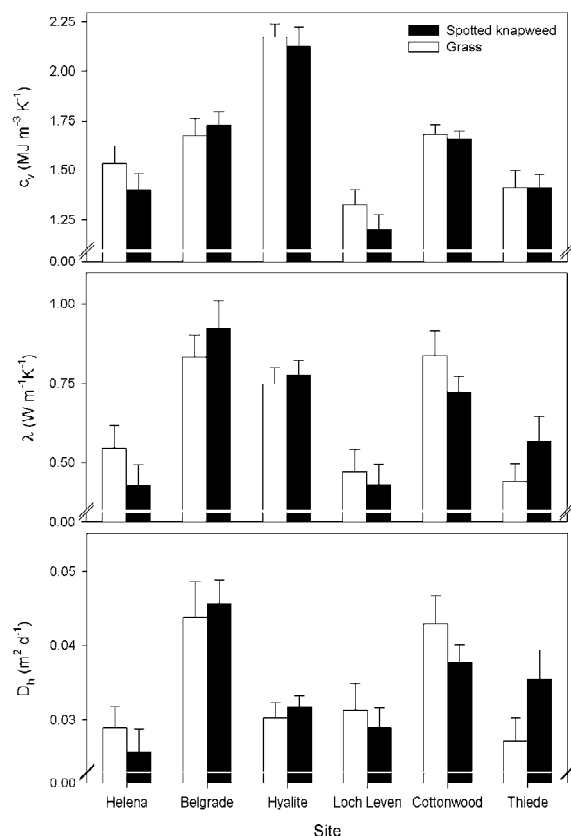


Figure 2. (a) Near-surface soil volumetric heat capacity (c_v), (b) thermal conductivity (λ), and (c) thermal diffusivity (D_h) (mean \pm SE; $n=4$; Thiede $n=8$) for *C. maculosa* and native grass plots.

were absent or, in a few cases where present, were inconsistent among blocks at most sites and among sites. Presumably, this inconsistency reflects the inherently high spatial variability of these properties (Mulla and McBratney, 2000), relative to any effects of vegetation type.

The slightly greater sand fractions in near-surface soils at Helena and Belgrade might indicate redistribution of surface soil by wind or water at these sites. However, this seems unlikely because if surface soil is redistributed, total organic carbon content of surface soils should also differ (Hook et al., 1991), but total organic carbon content was similar for *C. maculosa* and native grass plots at each site.

Lower bulk density in *C. maculosa* plots at Helena was not expected because these plots had a greater sand fraction, which should contribute to higher bulk density. Small differences in bulk density which may develop at the soil surface in response to differences in rainfall impact or other vegetative influences may

not be detected using the 0–5 cm depth. Consistent with the measured bulk densities, soil hydraulic and thermal properties were generally similar for native grass and *C. maculosa* plots, which indicates that soil characteristics immediately at the soil surface that influence these properties (including bulk density) were similar.

Saturated hydraulic conductivity is strongly influenced by soil pore size distribution and pore continuity, which can be affected by plant root characteristics through soil aggregation and root biopore formation (Hamblin, 1985; Radcliffe and Rasmussen, 2000). The tap-rooted *C. maculosa* and the fibrous-rooted native grasses did not produce consistent differences in saturated hydraulic conductivity or range in water conducting pore sizes based on α .

Soil thermal properties were also highly variable and inconsistent. Because air has low thermal conductivity, soil thermal conductivity increases with bulk density and depends on soil water content (Hillel, 1998). At most sites, differences in thermal conductivity were generally consistent with differences in bulk density. The influences of soil water content, bulk density, organic matter content, and their possible combined effects on thermal properties makes isolating vegetative impacts problematic. Our results indicated that areas dominated by *C. maculosa* do not have a more extreme near-surface soil thermal environment than grass-dominated areas because amplitudes of near-surface soil temperature fluctuations were similar between these types. Further, native grass plots had higher mean daily near-surface soil temperatures than *C. maculosa* plots. The greater mean daily surface soil temperatures in native grass plots may reflect lower LAI in these areas.

Our results indicate that *C. maculosa* did not alter near-surface soil physical properties within or among the six field sites. This agrees with Lacey et al. (1989) who found greater surface runoff and sediment yield with simulated rainfall for areas dominated by *C. maculosa* than areas dominated by a native grass. After removing aboveground plant material and repeating the rainfall, surface runoff and sediment yield were similar, indicating their initial runoff and sediment yield reflected differences in plant structure and canopy cover rather than altered soil properties. Infiltration can be influenced by differences in canopy structure associated with native grasses, forbs, and shrubs (e.g., Gutierrez and Hernandez, 1996; Meeuwig, 1970; Pearse and Woolley, 1936). Canopy structure affects raindrop impact, retention of rainfall

in canopies, and other factors. In this study, greater LAI in *C. maculosa*-dominated areas indicates that the potential for soil erosion would not be increased by this invasive plant species.

Specific vegetative impacts on soil properties are difficult to determine because of intricate relationships between these properties and their unknown rates of change in wildland soils. Because we did not measure systematic differences for the soil physical properties studied, we presume that seed germination or seedling growth of dominant native species would not be affected by altered soil water behavior, erosion potential, or thermal regimes.

The specific invasion history of *C. maculosa* at each site is unknown, because landowners or land managers were not cognizant of the changes in vegetative composition until they became appreciable. Total organic carbon content and bulk density can differ following tree and shrub removal after only 55 months (Albaladejo et al., 1998). Because of its different aboveground, and particularly belowground morphology, we speculate that *C. maculosa* might ultimately alter surface soil properties relative to native grasses, but it may take substantially longer than one or two decades for these changes to be detected.

Sites in this study do not represent the entire spectrum of sites that *C. maculosa* invades. Results might have been more (or less) consistent on sites with stonier soils or steeper slopes, or which are heavily grazed. The dominant grazers in western North America (cattle) prefer native grasses and avoid *C. maculosa*, thereby they alter competitive relations between native grasses and *C. maculosa*, and may trample and compact the soil surface in grass-dominated areas. Nevertheless, our results are important because they document the lack of measurable changes in selected soil physical properties on six different field locations invaded by *C. maculosa*. Invasive success of *C. maculosa* in these areas must therefore be a result of factors other than altered soil physical properties and the subsequent potential impacts on various related soil processes.

Conclusions

Presence of *C. maculosa* for at least five years (based on plant age) and likely for decades (based on landowner reports) did not alter near-surface soil characteristics at six disparate field sites. A few soil properties differed between *C. maculosa* and native

grass plots, but differences were inconsistent within and among sites, and between *C. maculosa* and native grasses. High spatial variability associated with soil physical properties and complex interactions among different soil properties do not allow us to directly assess plant species' impacts on soil properties or processes. However, results from the six field sites in this study do not support assertions that the invasive *C. maculosa* degrades soils. If such effects occur, they are relatively weak or require more time to develop. Further, our findings indicate that physical attributes of soils would not need to be ameliorated in order to prepare sites for restoring native perennial grasses following eradication of *C. maculosa*.

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